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Detection of gear pitting failure progression with on-line particle monitoring

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ABSTRACT

Macroscopic pitting is a common gear flank failure mode. The determination of pitting life is done experimentally and the formation of macropit is typically followed by regular visual inspections and photographing of tooth flanks, which is time consuming and gives limited information about progression of failure. In this study, the progression of gear macropitting was detected with on-line particle monitoring from lubricating oil together with vibration monitoring and visual inspections. The tests were carried out with case-hardened gears under heavy loading condition. The results show that the concentration of metallic particles in oil correlate well with the severity of macropitting obtained from the visual inspection. Vibration acceleration descriptors indicating peaked signal correlate also with the wear of gear contact.

1. Introduction

Macroscopic pitting is one of the most common gear flank failure modes mainly caused by repetitive Hertzian contact stresses of the mating surfaces. This may cause fatigue cracks initiating from the surface or nearby subsurface leading to the detachment of a macropit. Macropits usually appear at dedentum tooth flank, where both stress and sliding velocity are high [1]. The determination of gear pitting life is done experimentally and the formation of macropit is typically followed by regular visual inspections and photographing of tooth flanks. Visual inspection is pretty time consuming and gives information only from one single time moment. In addition, it is often very challenging to estimate proper inspection intervals especially at the end of the test, when pitting process starts to be progressive. Fundamental knowledge of pitting as well as practical testing procedure would be improved if continuous information related to the progression of pitting failure is available.

Wear of gear pair is challenging to measure directly without disturbing the running contact state and lubrication condition. Indirect methods based on, for example, temperature, acoustic, vibration and oil particle contamination has been used to detect the symptoms of failure caused by wear. Ferrography and spectrometric methods [2–4] are known to be powerful tools for identifying wear degree and mechanism, but as off-line methods based on analysis of oil samples, they are considered to be too time consuming, laborious and hence providing too delayed information. In on-line and in-line particle monitoring, the detached pits or other solid contaminants in lubricating oil is detected continuously with specific sensors at gearbox outlet proving real time information. The on-line particle monitoring methods can typically detect the amount of particles and classify them to different size classes, but are missing of the ability to detect the shape of the particles. Salgueiro et al. [5] applied an electromagnetic metallic particle sensor, that counts ferrous particles of size ranges from 40 to 300 μm, to monitor the pitting test in single-stage gear box and concluded that the amount of wear particles followed the trend of load level. Feng et al. [6] predicted wear of a spur gearbox and observed early-warning signs of abnormal wear behavior related to pitting and scuffing by employing an on-line visual ferrograph with an index of particle coverage area to characterize wear debris concentration. Martin [7] studied oil contaminants usually found from machines and engines by using digital imaging and digital shape recognition and concluded that it was possible to separate reliably real wear particles from other contaminants like bubbles and drops. This gives also the possibility to make form and particle size analysis for wear particles. Iwai et al. [8] determined wear quantity of against each other rubbing components with on-line particle monitoring based on number of particles and their sizes. The used method correlated well with the measured values of mass loss of the specimen. However, lubricating oil can contain some other contaminants which decrease the accuracy of real wear particle counting. Sugimura et al. [9] used wear image analysis in wear debris analysis to characterize different progress of wear in gears.

Most suitable methods for observing continuously the wearing of gears are particle and vibration monitoring. Vibration monitoring can

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be used to indicate the gear flank geometry changes due to the wear, for example, in the form of detached pits. In gear operation monitoring typically the amplitude of meshing frequency, number and amplitudes of meshing frequency sidebands, amplitude and multiples of rotational frequencies of shafts and resonance frequencies are measured [10]. The amplitude of meshing frequency is mainly proportional to the loading but not to the fault severity of the gear contact. The sideband frequencies above and below of the meshing frequency tell that there are some problems in running of the gears. Sidebands are generated by amplitude modulation, where the modulating frequency is typically the rotational frequency of one or both shafts and carrier frequency is the meshing frequency. The number and amplitudes of sidebands correlate with the severity of the fault in gear wheel. Normally some low amplitude sidebands can exist also in gear transmission which is in good condition. Typically, the trend of sidebands is monitored. The advantages of vibration monitoring compared to oil particle monitoring are simple sensor installations and simple usage even if the prices of the equipment are very close to each other. Difficulties come up in symptom extraction i.e. to determine suitable descriptors for computing from vibration signal to describe right phenomena. Local wear in gear wheel surface causes local starved lubrication situations. These kinds of phenomena and wear particles in lubrication oil generate in addition to cyclic vibration also random vibration. Random vibration signal can be analysed with several statistical descriptors, which indicate the level of the signal and if the signal is peaked [11].

It has been shown by many research studies that gear damage can be predicted more reliably by combining on-line particle and vibration monitoring methods [12–14]. Shah et al. [15] used on-line and off-line oil analysis connected to vibration measurement in condition monitoring of spur gears. Oil analysis consists of on-line particle counting and oil condition and moisture measurement. On-line oil analysis results were verified with off-line methods like analytical ferrography and SEM methods. Vibration analyses contained time synchronous averaging and spectrum methods combined to amplitude modulation phenomenon. Main result was that combining oil particle analysis and vibration analysis techniques gives more reliable condition monitoring, even if vibration analysis needs deep understanding of the frequency responses of gear transmission components. Dempsey [16,17] combined oil debris monitoring and vibration analysis in machine health monitoring. They found that oil debris monitoring cannot discriminate between gear and bearing failure. Loutas et al. [13] combined acoustic emission monitoring with oil debris and vibration monitoring.

The main objectives of this study are to detect the progression of gear macropitting failure with on-line particle monitoring from lubricating oil and its correlation to the corresponding results obtained with vibration monitoring from the test gearbox and with visual inspection documented by photographs. The tests were carried out with modified FZG gear test rig with real gears and operating condition.

2. Experiments

2.1. Test device

Gear tests were carried out using a modified FZG test device, which is shown in (Fig. 1). The loading of the test gears can be adjusted by applying appropriate torque to shaft 1 through the load clutch using weights and a rod. The applied torque is measured on-line from shaft 1 with strain gages and telemetry device. The required power is fed with an electric motor, of which adjustable rotating speed is controlled by frequency converter. The rotational speed is measured from shaft 2 with a pulse sensor. The system friction torque is measured with torque transducer from shaft 2.

2.2. Test gears and lubricants

The material of the test gears is case hardened steel 18CrNiMo7-6. The gears are case hardened to a depth of 1.0–1.3 mm, with specific surface hardness of 60–62 HRC. After hardening the gears were ground resulting in the flank Ra surface roughness in the range of 0.46 – 0.52 μm. The main features of the test gears are shown in Table 1. The test gears have modifications in the axial and profile directions.

The test lubricant was synthetic gear oil ISO VG 320 with kinematic viscosity at 40 and 100 °C of 335 and 38.3 mm^2/s, respectively. The density of the lubricant at 15.6 °C was 860 kg/m^3. The tests were carried out with oil inlet temperature of 60 °C and lubricant flow rate of 2.0 l/min.

2.3. Particle monitoring

The gears and bearings are lubricated using pressurized circulating (spray) lubrication so that the spray is directed with the direction of rotation of gears as shown in Fig. 1. The test and slave gears have their own lubricating systems. The flow chart of the lubrication system of the test gearbox is shown in Fig. 2. Oil fed into the test gearbox is filtrated with 6 μm filter. Cleanliness of the inlet oil is measured from a side flow using an optical particle counter. Particles larger than effective diameter of 4 μm are detected and the results are classified to three different size classes according to ISO 4406 standard. Particles in outlet oil are observed on-line with an inductive metallic contaminant sensor. Ferrous particles larger than the effective diameter of 70 μm and non-ferromagnetic metallic particles larger than the effective diameter of 200 μm are detected. The sampling intervals of the particle monitoring in both cases are one minute.

2.4. Vibration monitoring

The primary target of vibration monitoring was to find out if the progression of pitting is detected with vibration measurements. The other target of vibration measurements was to monitor possible phenomena which are not connected to the gear wheel pitting. These kinds of phenomena are gear wheel misalignment, different kind of looseness and rolling bearing failures. Combining vibration and oil particle monitoring and other running parameter monitoring and photographing may offer more reliable view about the progression of pitting.

The measured parameter was vibration acceleration. Sensor was a piezoelectric accelerometer model B & K 4382. It was installed on the test gear box and fixed with magnet fixing. The +10% frequency range of the sensor is 8.4 kHz, but magnet fixing may a little bit reduce the useful frequency band of the sensor. The meshing frequency of the gear transmission was 600 Hz. Standards e.g. PSK 5719 [10] recommend that the upper frequency limit should be minimum 3.25 times meshing frequency, which in this case means frequency of 1.95 kHz. The sampling rate in measurements was 10 kHz and results were analysed in area of 5 Hz ... 5 kHz in different frequency bands. The descriptors computed from measurement results are presented in Table 2.

Kurtosis and Crest Factor indicate if the signal is peaked or flat. RMS value indicates vibration acceleration overall level and Form Factor indicates the relationship of RMS and average value. In addition to these values the spectra in the area of meshing frequency was analysed.

2.5. Test procedure

At first the lubricant was circulated through the test device and warmed up to the test temperature in time of minimum of two hours. Running-in was started by setting the rotating speed of 1500 rpm to the shaft 2 and increasing the load stages with 8 steps ranging from 3 to 239 Nm, each step having a time interval of 10 min. After running-in the steady-state operating conditions was maintained with the load level of 405 Nm and wheel speed of 1500 rpm. The test rig was stopped